MULTIPLE OUTPUT CONVERTER AND METHOD OF OPERATION THEREOF

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MULTIPLE OUTPUT CONVERTER AND METHOD OF OPERATION THEREOF

TECHNICAL FIELD OF THE INVENTION

[0001]   This invention relates to the field of power electronics and, more particularly, to a multiple output converter and method of operation thereof.

BACKGROUND OF THE INVENTION

[0002]   A converter is a processing circuit that converts an input voltage or current source waveform into a specified output voltage or current waveform. A buck-derived switching converter (also referred to as a "buck converter") is a frequently employed converter that converts a direct current (DC) input waveform to a specified DC output waveform. A characteristic of buck converters, in general, is that the DC output waveform is less than the DC input waveform. A buck converter that does not employ a transformer as an isolation stage is referred to as a non-isolated buck converter. The non-isolated buck converter typically includes switching circuitry coupled to an input source of electrical power. The switching circuitry includes at least one active switch. The switching circuitry is coupled to an output inductor and output

capacitor which provides the DC output waveform (*i.e.*, an output voltage) at an output of the non-isolated buck converter.

[0003] Multiple output switching converters are often employed to provide multiple output voltage levels driving independent loads at varying current levels. In some cases, the output voltage levels may be reversed in polarity (*e.g.*, +12 volts and -12 volts) and referenced to a common return. With regard to switching converters that include an isolation stage, the multiple output voltages may be provided via multiple windings on the secondary side of a transformer. In non-isolated switching converters (*e.g.*, non-isolated buck converters), however, deriving multiple output voltages, irrespective of the level and polarity of the voltages, is more complex to implement and may impact the overall efficiency of the switching converters.

[0004] Presently, a second output voltage may be derived from a multiple output non-isolated buck converter via an inductor. Under such circumstances, the second output voltage is rectified through a rectifier (*e.g.*, a diode rectifier or synchronous rectifier) and post regulated to deliver the second output voltage at an auxiliary output of the multiple output non-isolated buck converter. While employing yet another technique, a second output voltage may be derived from a multiple output non-isolated buck converter by employing a charge pump therein.

[0005] While the aforementioned techniques have proven beneficial, the approaches suffer from the foregoing limitations. The technique of using the inductor for the purpose of providing multiple output voltages in the multiple output non-isolated buck converter typically employs either a peak charge rectified or forward rectified outputs that may suffer from significant ripple currents associated with the primary and auxiliary outputs of the converter. Even for smaller currents, series damping is generally a prerequisite, along with a large inductor to account for the peak currents and ripple condition associated with the primary and auxiliary outputs of the converter. Thus, the design generally calls for larger magnetic components within the multiple output non-isolated buck converter. Charge pumps, on the other hand, have restrictions on current outputs relative to the respective footprints. Therefore, the present techniques and methods of generating the second output voltage still call for larger surface area magnetic devices.

[0006] Accordingly, what is needed in the art is a circuit and method that maintains regulation of the output voltages for a multiple output converter such as a multiple output non-isolated buck converter, while preserving the overall efficiency of the converter.

SUMMARY OF THE INVENTION

[0007]   To address the above-discussed deficiencies of the prior art, the present invention provides a multiple output converter that includes a primary output and at least one auxiliary output. In one embodiment, the multiple output converter includes a transformer having a primary winding and at least one secondary winding. The multiple output converter also includes a switch, coupled to the primary winding, that impresses an input voltage across the transformer. A first output voltage of the multiple output converter is produced at the primary output via a magnetizing inductance associated with the transformer. The multiple output converter still further includes an output inductor coupled to the at least one secondary winding. A second output voltage of the multiple output converter is produced at the auxiliary output coupled via the output inductor.

[0008]   In another aspect, the present invention provides a method of operating a multiple output converter including a primary output and at least one auxiliary output. In one embodiment, the method includes providing a transformer having a primary winding and at least one secondary winding. The method also includes impressing an input voltage across the transformer with a switch coupled to the primary winding. The method further includes producing a first output voltage at the primary output via a

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magnetizing inductance associated with the transformer. The method still further includes producing a second output voltage at the auxiliary output via an output inductor coupled to the at least one secondary winding.

[0009]   The foregoing has outlined, rather broadly, preferred and alternative features of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art should appreciate that they can readily use the disclosed conception and specific embodiment as a basis for designing or modifying other structures for carrying out the same purposes of the present invention. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]   For a more complete understanding of the present
invention, reference is now made to the following descriptions
taken in conjunction with the accompanying drawings, in which:

[0011]   FIGURE 1 illustrates a schematic diagram of an embodiment
of a multiple output converter constructed according to the
principles of the present invention;

[0012]   FIGUREs 2A-2F illustrate waveform diagrams of an
exemplary operation of the multiple output converter of FIGURE 1 at
selected operating conditions according to the principles of the
present invention;

[0013]   FIGUREs 3A-3F illustrate waveform diagrams of another
exemplary operation of the multiple output converter of FIGURE 1 at
selected operating conditions according to the principles of the
present invention;

[0014]   FIGUREs 4A-4F illustrate waveform diagrams of another
exemplary operation of the multiple output converter of FIGURE 1 at
selected operating conditions according to the principles of the
present invention;

[0015]   FIGUREs 5A-5F illustrate waveform diagrams of another
exemplary operation of the multiple output converter of FIGURE 1 at
selected operating conditions according to the principles of the
present invention;

[0016]   FIGUREs 6A-6F illustrate waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention;

[0017]   FIGUREs 7A-7F illustrate waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention;

[0018]   FIGURE 8 illustrates a diagram demonstrating a series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention;

[0019]   FIGURE 9 illustrates a diagram demonstrating a series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention;

[0020]   FIGURE 10 illustrates a diagram demonstrating a relationship between a primary duty cycle and output voltages of the multiple output converter according to the principles of the present invention;

[0021]   FIGURE 11 illustrates a waveform diagram of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention; and

[0022]   FIGURE 12 illustrates a waveform diagram of another series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention.

DETAILED DESCRIPTION

[0023] Referring initially to FIGURE 1, illustrated is a schematic diagram of an embodiment of a multiple output converter (e.g., multiple output buck converter) constructed according to the principles of the invention. The multiple output converter is coupled to a source of electrical power that provides an input voltage V_{in} and includes first and second switches Q_1, Q_2 coupled to a primary winding PR of a transformer T_1. The transformer T_1 has a magnetizing inductance L_{mag} and serves as an inductor associated with a primary output of the multiple output converter. The primary winding PR preferably has a gapped core to generate a requisite inductance value and a number of turns represented by N_p.

[0024] The transformer T_1 also includes first and second secondary windings SEC_1, SEC_2 coupled to a rectifier (e.g., a synchronous rectifier formed by first and second synchronous rectifier switches SR_1, SR_2) and having a number of turns represented by N_{S1}, N_{S2}, respectively. The primary winding PR is coupled, via the magnetizing inductance L_{mag} to a first output capacitor C_{out1} that provides a first output current I_{out1} at a first output voltage V_{out1} at the primary output of the multiple output converter. The first and second synchronous rectifier switches SR_1, SR_2 are coupled to an output inductor L_{out} and a second output capacitor C_{out2} that provides a second output current I_{out2} at a

second output voltage V_{out2} at an auxiliary output of the multiple output converter.

[0025] The multiple output converter generally operates as set forth below. During a primary interval, a controller (e.g., a pulse width modulation controller) CL_{PWM} monitors the first output voltage V_{out1} and causes the first switch Q_1 to conduct for a primary duty cycle (D) to apply a voltage equal to a difference between the input voltage V_{in} of the first output voltage V_{out1} across the primary winding PR. The controller CL_{PWM}, then, transitions the first switch Q_1 to a non-conducting state and, during a complementary interval, causes the second switch Q_2 to conduct for a complementary duty cycle (1-D). During the complementary interval, an opposite polarity of the input voltage V_{in} is applied across the primary winding PR. The controller CL_{PWM}, therein, monitors the first output voltage V_{out1} and controls a duty cycle of the first and second switches Q_1, Q_2 to maintain the first output voltage V_{out1} and, ultimately, the second output voltage V_{out2}, at the desired values.

[0026] Thus, the switching action of the first and second switches Q_1, Q_2 converts a DC input voltage V_{in} into an AC voltage necessary to operate the transformer T_1. Additionally, a first output current I_{out1} at a first output voltage V_{out1} is provided via the magnetizing inductance L_{mag} of the transformer T_1 at the primary output of the multiple output converter. The first output

capacitor C_{out1} filters the first output voltage V_{out1} at the primary output. The first and second secondary windings SEC_1, SEC_2 of the transformer T_1 scale the AC voltage to an appropriate value. The scaled AC voltage is then rectified by the synchronous rectifier and filtered by the second output capacitor C_{out2}. A second output current I_{out2} at a second output voltage V_{out2} is provided via the output inductor L_{out} at the auxiliary output of the multiple output converter. Regarding the operation of the controllable switches of the multiple output converter, the first switch Q_1 and the second synchronous rectifier switch SR_2 primarily conduct during the primary interval of the multiple output converter. Conversely, the second switch Q_2 and the first synchronous rectifier switch SR_1 primarily conduct during the complementary interval of the multiple output converter.

[0027] For a better understanding of the multiple output converter, a more detailed analysis thereof will hereinafter be described. Prior to analyzing the multiple output converter, an objective in designing the converter is to provide multiple regulated output voltages, while at the same time, maintaining a ripple condition within the multiple output converter and a net DC bias across the transformer T_1 within acceptable limitations. If the ripple condition and net DC bias are not adequately maintained, the magnetic devices (*i.e.*, the transformer T_1 and output inductor L_{out}) may become prohibitively larger (including a potential for a

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core with a large gap) or dampening circuits (such as snubber circuits) may be required in the multiple output converter. As the real estate for the converters continues to shrink and the efficiency targets increase, the aforementioned mitigatory options are becoming less viable. Thus, the multiple output converter is designed, among other things, to manage both the ripple and net DC bias conditions.

[0028] Turning now to the operation of the multiple output converter, the first output voltage V_{out1} may be described as follows:

$$V_{out1} = D * V_{in},$$

wherein D represents the duty cycle (also referred to as the primary duty cycle) of the first switch Q_1. The second output voltage V_{out2} may be described as follows:

$$V_{out2} = V_{out1} * (1-D) [(N_{S1} + N_{S2})/N_P],$$

wherein (1-D) represents the duty cycle (also referred to as the complementary duty cycle) of the second switch Q_2. Thus, as the primary duty cycle D of the first switch Q_1 increases, the first output voltage V_{out1} also increases.

[0029] Also, as the primary duty cycle D increases between zero and 50 percent, the complementary duty cycle (1-D) of the second switch Q_2 decreases from 100 to 50 percent and the second output voltage V_{out2} increases. Conversely, as the primary duty cycle D increases from 50 to 100 percent, the complementary duty cycle (1-

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D) of the second switch Q_2 decreases from 50 to zero percent and the second output voltage V_{out2} also decreases. This parabolic response of the second output voltage V_{out2} to the primary duty cycle D is due, in part, to the functional dependence on the primary and complementary duty cycles D, (1-D).

[0030]   Additionally, regulating the first output voltage V_{out1} leads to a proper regulation of the second output voltage V_{out2} in accordance with selecting the primary and complementary duty cycles D, (1-D) of the first and second switches Q_1, Q_2, respectively, as hereinafter described. From the relationships above, the primary duty cycle D of the first switch Q_1 may be described as follows:

$$D = \frac{1}{2} \pm \frac{1}{2} * SQR \left\{ 1 - 4V_{out2}/V_{in} * N_P/(N_{S1} + N_{S2}) \right\}.$$

[0031]   To achieve substantial ripple cancellation on a secondary side of the multiple output converter and within the converter in general, the following relationship:

$$(1-D) * V_{in} (N_{S2}/N_P) = D * V_{in} (N_{S1}/N_P),$$

is solved for the primary duty cycle D of the first switch Q_1, yielding:

$$D = N_{S2} / (N_{S1} + N_{S2}).$$

Moreover, under such conditions, the second output voltage V_{out2} may be described by the following relationship:

$$V_{out2} = V_{in} \left\{ (N_{S1} * N_{S2})/[N_P * (N_{S1} + N_{S2})] \right\}.$$

Thus, the second output voltage V_{out2} is a function of the input voltage V_{in} and the number of turns N_P, N_{S1}, N_{S2} of the primary

winding PR and the first and second secondary windings SEC_1, SEC_2, respectively, of the transformer T_1.

[0032]   A magnetizing current I_{mag} of the transformer T_1 may be represented by :

$$I_{mag} = I_{magDC} + I_{magAC},$$

wherein I_{magDC} is the DC component of the magnetizing current I_{mag} and I_{magAC} is the AC component of the magnetizing current I_{mag}. All components of the magnetizing current I_{mag} herein are referenced to a primary side of the transformer T_1. The DC component I_{magDC} of the magnetizing current I_{mag} may be represented by:

$$I_{magDC} = I_{magDC1} + I_{magDC2},$$

wherein I_{magDC1} is a DC bias current associated with a primary side of the multiple output converter (which is equal to the first output current I_{out1} in the illustrated embodiment), and I_{magDC2} is a DC bias current associated with a secondary side of the multiple output converter.

[0033]   Another set of relationships are evaluated to analyze the net DC bias across the transformer T_1. The analysis begins with the DC bias current I_{magDC2} associated with the secondary side of the multiple output converter as set forth below:

$$I_{magDC2} = [N_{S1}/N_P * I_{out2}] - [D * (N_{S1} + N_{S2})/N_P * I_{out2}].$$

It should be understood that the DC bias current I_{magDC2} associated with the secondary side of the multiple output converter across the transformer T_1 may be either a positive or negative value. The DC

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bias current I_{magDC2} associated with the secondary side of the multiple output converter is added to the DC bias current I_{magDC1} associated with the primary side of the multiple output converter (which, again, is the first output current I_{out1}) to yield the DC component I_{magDC} (also referred to as a net DC bias current) of the magnetizing current I_{mag} represented by:

$$I_{magDC} = I_{out1} + [N_{S1}/N_P * I_{out2}] - [D * (N_{S1} + N_{S2})/N_P * I_{out2}].$$

Employing the above relationship to ascertain the primary duty cycle D of the first switch Q_1 for a substantially zero DC bias current I_{magDC2} associated with the secondary side of the multiple output converter provides the following relationship:

$$D = N_{S1} / (N_{S1} + N_{S2}).$$

Thus, if the primary duty cycle D of the first switch Q_1 is greater than the value of the turns ratio as described above, the DC bias current I_{magDC2} associated with the secondary side of the multiple output converter across the transformer T_1 is negative.

[0034]   It is also possible to select the primary duty cycle D of the first switch Q_1 to achieve both substantial ripple cancellation and a substantially zero net DC bias current I_{magDC} across the transformer T_1. More specifically, by selecting the primary duty cycle D of the first switch Q_1 according to:

$$D = N_{S2} / (N_{S1} + N_{S2}),$$

a substantial ripple cancellation in the secondary side of the multiple output converter and the converter in general can be

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achieved. The DC bias current I_{magDC2} associated with the secondary side of the multiple output converter may be negative. The negative value of the DC bias current I_{magDC2} associated with the secondary side of the multiple output converter may be offset by a positive DC bias current I_{magDC1} associated with the primary side of the multiple output converter thereby providing a substantially zero net DC bias current I_{magDC} across the transformer T_1 of the multiple output converter.

[0035] The advantages of designing the multiple output converter under such conditions provides an overall reduction in the size of the magnetic components thereof. More specifically, the output inductor L_{out} may be downsized because the magnetic device does not have to accommodate a substantial ripple current in the secondary side of the multiple output converter. Additionally, the transformer T_1 may not need a substantial gap, if any at all, in the magnetic core thereof to accommodate a large net DC bias thereacross. Mitigating the need for a substantial gap in the core of the transformer T_1 allows for several advantages such as a substantially larger magnetizing inductance L_{mag} for a given size of a magnetic device. Additionally, a larger magnetizing inductance L_{mag} could be applied to filter the first output voltage V_{out1} of the multiple output converter.

[0036] An exemplary design will hereinafter be described to demonstrate the principles as stated above. The following values

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are submitted in Table I below for selected components of the multiple output converter:

TABLE I

Parameter/Component	Reference	Value
Input Voltage	V_{in}	18 volts
Number of turns of the primary winding PR	N_P	3
Number of turns of the first secondary winding SEC_1	N_{S1}	3
Number of turns of the second secondary winding SEC_2	N_{S2}	6
Switching frequency of the first and second switches Q_1, Q_2	f	300 kHz
First output voltage	V_{out1}	12 volts
First output current	I_{out1}	5 amps
Second output voltage	V_{out2}	12 volts
Second output current	I_{out2}	1 amp
Primary duty cycle of the first switch Q_1	D	0.67
Complementary duty cycle of the second switch Q_2	1-D	0.33

[0037]   Employing the values as stated above for selected components yields substantial ripple cancellation in the secondary side of the multiple output converter thereby allowing the output inductor L_{out} to be relatively small (e.g., 1 μH). Additionally, the DC bias current I_{magDC2} associated with the secondary side of the multiple output converter is about a negative one amp resulting in a DC component I_{magDC} of the magnetizing current I_{mag} of a positive four amps thereby allowing for a larger inductance (e.g., 4 μH) in a smaller core than would have been possible with an unbiased DC component I_{magDC} of the magnetizing current I_{mag} of a positive five amps. As a result, the size of the transformer T_1 and the output inductor L_{out} are relatively small in comparison to other converters attempting to provide analogous power under like conditions. Taking the design a step further, if the first output current I_{out1} at the primary output is limited to one amp, it is possible to achieve a substantially zero DC component I_{magDC} of the magnetizing current I_{mag} across the transformer T_1 thereby further reducing the gap, or removing it altogether, in the core thereof.

[0038]   The following FIGUREs and associated discussions provide waveform diagrams of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions. Unless otherwise noted, the parameters/component values are as submitted above in Table I.

[0039]   Turning now to FIGUREs 2A-2F, illustrated are waveform diagrams of an exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention.   More specifically, the primary output provides a first output current I_{out1} of five amps at a first output voltage V_{out1} of 12 volts and the auxiliary output provides a second output current I_{out2} of one amp at a second output voltage V_{out2} of 12 volts.

[0040]   As illustrated by FIGURE 2A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is a positive four amps which is less than an unbiased DC component I_{magDC} of the magnetizing current I_{mag} of a positive five amps. Furthermore, as illustrated by FIGUREs 2C and 2D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}.   Additionally, as illustrated by FIGUREs 2E and 2F, the first output current I_{out1} and first output voltage V_{out1} at the primary output also exhibit a small ripple condition.

[0041]   Turning now to FIGUREs 3A-3F, illustrated are waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention.   More specifically, the primary output provides a first output current I_{out1} of five amps at a first output voltage V_{out1} of 12 volts and the auxiliary output

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provides a second output current I_{out2} of zero amps at a second output voltage V_{out2} of 12 volts.

[0042] As illustrated by FIGURE 3A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is a positive five amps. Furthermore, as illustrated by FIGUREs 3C and 3D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}. Additionally, as illustrated by FIGUREs 3E and 3F, the first output current I_{out1} and first output voltage V_{out1} at the primary output also exhibit a small ripple condition.

[0043] In comparison to the operating conditions illustrated and described with respect to FIGUREs 2E and 2F, the waveform diagrams of FIGUREs 3E and 3F demonstrate a reduced ripple condition for the first output current I_{out1} and first output voltage V_{out1}. The relatively larger ripple condition for the first output current I_{out1} and first output voltage V_{out1} illustrated in FIGUREs 2E and 2F may be attributed to a switching of a substantially non-zero current on the secondary side of transformer T_1.

[0044] Turning now to FIGUREs 4A-4F, illustrated are waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the primary output provides a first output current I_{out1} of zero amps at a first output voltage V_{out1} of 12 volts and the auxiliary output

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provides a second output current I_{out2} of zero amps at a second output voltage V_{out2} of 12 volts.

[0045]   As illustrated by FIGURE 4A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is zero amps thereby providing a substantially zero net DC bias across the transformer T_1. Furthermore, as illustrated by FIGUREs 4C and 4D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}. Additionally, as illustrated by FIGUREs 4E and 4F, while the first output current I_{out1} demonstrates a zero ripple current, the first output voltage V_{out1} at the primary output exhibits a small ripple voltage.

[0046]   Turning now to FIGUREs 5A-5F, illustrated are waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the primary output provides a first output current I_{out1} of zero amps at a first output voltage V_{out1} of 12 volts and the auxiliary output provides a second output current I_{out2} of one amp at a second output voltage V_{out2} of 12 volts.

[0047]   As illustrated by FIGURE 5A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is a negative one amp. Furthermore, as illustrated by FIGUREs 5C and 5D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}. Additionally,

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as illustrated by FIGUREs 5E and 5F, while the first output current I_{out1} demonstrates a zero ripple current, the first output voltage V_{out1} at the primary output exhibits a small ripple voltage.

[0048] In comparison to the operating conditions illustrated and described with respect to FIGURE 2C, the waveform diagram of FIGURE 5C demonstrates a reduced inductor ripple current I_{Lout}. The relatively larger inductor ripple current I_{Lout} illustrated in FIGURE 2C may be attributed to switching of a substantially non-zero current on the primary side of transformer T_1.

[0049] Turning now to FIGUREs 6A-6F, illustrated are waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the primary output provides a first output current I_{out1} of one amp at a first output voltage V_{out1} of 12 volts and the auxiliary output provides a second output current I_{out2} of zero amps at a second output voltage V_{out2} of 12 volts.

[0050] As illustrated by FIGURE 6A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is a positive one amp. Furthermore, as illustrated by FIGUREs 6C and 6D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}. Additionally, as illustrated by FIGUREs 6E and 6F, the first output current I_{out1}

and first output voltage V_{out1} at the primary output also exhibit a small ripple condition.

[0051] Turning now to FIGUREs 7A-7F, illustrated are waveform diagrams of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the primary output provides a first output current I_{out1} of one amp at a first output voltage V_{out1} of 12 volts and the auxiliary output provides a second output current I_{out2} of one amp at a second output voltage V_{out2} of 12 volts.

[0052] As illustrated by FIGURE 7A, a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1 is zero amps (which is less than an unbiased DC component I_{magDC} of the magnetizing current I_{mag} of a positive one amp) thereby providing a substantially zero net DC bias across the transformer T_1. Furthermore, as illustrated by FIGUREs 7C and 7D, the output inductor L_{out} demonstrates a small inductor ripple current I_{Lout} and small inductor ripple voltage V_{Lout}. Additionally, as illustrated by FIGUREs 7E and 7F, the first output current I_{out1} and first output voltage V_{out1} at the primary output also exhibit a small ripple condition.

[0053] Turning now to FIGURE 8, illustrated is a diagram demonstrating a series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions

according to the principles of the present invention. More specifically, the diagram of FIGURE 8 illustrates a net DC bias flux density of the transformer T_1 as a function of a first output current I_{out1} associated with the primary output when the auxiliary output provides a second output current I_{out2} of one amp at a second output voltage V_{out2} of 12 volts. As illustrated, a net DC bias flux density of the transformer T_1 is substantially zero when the first output current I_{out1} is one amp. At that operating condition, a substantially zero net DC bias flux associated with a substantially zero net DC bias current I_{magDC} is demonstrated across the transformer T_1.

[0054]   Turning now to FIGURE 9, illustrated is a diagram demonstrating a series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the diagram of FIGURE 9 illustrates a net DC bias flux density of the transformer T_1 as a function of a second output current I_{out2} associated with the auxiliary output when the primary output provides a first output current I_{out1} of one amp at a first output voltage V_{out1} of 12 volts. As illustrated, a net DC bias flux density of the transformer T_1 is substantially zero when the second output current I_{out2} is one amp. At that operating condition, a substantially zero net DC bias flux associated with a substantially

zero net DC bias current I_{magDC} is demonstrated across the transformer T_1.

[0055]   Turning now to FIGURE 10, illustrated is a diagram demonstrating a relationship between a primary duty cycle and output voltages of the multiple output converter according to the principles of the present invention.   More specifically, the diagram of FIGURE 10 illustrates output voltages associated with the primary and auxiliary outputs as a function of a primary duty cycle (D) of the first switch Q_1 of the multiple output converter employing the values submitted in Table I above.   As illustrated, a primary duty cycle D of 0.67 for the first switch Q_1 provides substantial ripple cancellation when the first and second output voltages V_{out1}, V_{out2} are 12 volts, the input voltage V_{in} is 18 volts, and the number of turns N_P, N_{S1}, N_{S2} for the primary winding PR, first secondary winding SEC_1 and second secondary winding SEC_2 of transformer T_1 are 3, 3, 6, respectively.

[0056]   Turning now to FIGURE 11, illustrated is a waveform diagram of another exemplary operation of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention.   More specifically, the waveform diagram of FIGURE 11 illustrates a first output voltage V_{out1} associated with the primary output as a function of time with the second output current I_{out2} of the auxiliary output providing one amp and zero amps, respectively.   As illustrated, a change in the

second output current I_{out2} affects a ripple condition associated with the first output voltage V_{out1}.

[0057] Turning now to FIGURE 12, illustrated is a waveform diagram of another series of exemplary operations of the multiple output converter of FIGURE 1 at selected operating conditions according to the principles of the present invention. More specifically, the waveform diagram of FIGURE 12 illustrates a magnetizing current I_{mag} of the transformer T_1 as a function of time over several operating conditions of the multiple output converter. As illustrated, different operating conditions, namely, a change in the first and second output currents I_{out1}, I_{out2} affect the magnetizing current I_{mag} of the transformer T_1. In accordance therewith, the different operating conditions affect a DC component I_{magDC} of the magnetizing current I_{mag} associated with the transformer T_1.

[0058] Thus, a multiple output converter, and related method of operation thereof, with readily attainable and quantifiable advantages has been introduced. Those skilled in the art should understand that the previously described embodiments of the multiple output converter and exemplary operating conditions are submitted for illustrative purposes only and that other converter embodiments capable of providing multiple outputs while addressing a ripple condition in the converter and a net DC bias associated

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with a transformer are well within the broad scope of the present invention.

[0059]   Exemplary embodiments of the present invention have been illustrated above with reference to specific electronic and magnetic components. Those skilled in the art are aware, however, that components may be substituted (not necessarily with components of the same type) to create desired conditions or accomplish desired results. For instance, multiple components may be substituted for a single component and vice-versa. Additionally, the multiple output converter illustrated and described herein includes two outputs, namely, the primary output and the auxiliary output. It should be understood by those skilled in the art, however, that the multiple output converter may have more than two outputs (e.g., a primary output and multiple auxiliary outputs) and still fall within the broad scope of the present invention. In such a case, a magnetizing current may be derived from a primary winding and multiple secondary windings associated with the transformer.

[0060]   For a better understanding of power electronics control systems, see Erickson, R. W., *Fundamentals of Power Electronics*, Chapman and Hall (1997). For a better understanding of power electronics and power converter topologies, see Kassakian, et al., *Principles of Power Electronics*, Addison-Wesley Publishing Company

(1991). The aforementioned references are incorporated herein by reference in their entirety.

[0061] Although the present invention has been described in detail, those skilled in the art should understand that they can make various changes, substitutions and alterations herein without departing from the spirit and scope of the invention in its broadest form.